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Research report

Hyperactive movement behaviour of athletes with post-concussion symptoms

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ABSTRACT

Objective: Observations of hyperactive (/restless, agitated) behaviour as a consequence of mild traumatic brain injuries (mTBI) in sports are inconclusive as reduced or slowed movement behaviour is also commonly described post-concussion. This might be grounded in the fact that the movement behaviour of athletes has not been systematically investigated during standardized settings and with objective methods of nonverbal movement analysis. Thus, we investigate whether symptoms after mTBI in sports are characterized by a hyper- or hypoactive movement behaviour experimentally.
Methods: Three matched groups of 40 athletes were investigated: 14 symptomatic and 14 asymptomatic athletes with a mTBI; and 12 non-concussed athletes. Four certified raters analysed with a standard analysis system for nonverbal behaviour each athlete's hand movement activity, hand movement contacts, and resting positions that were displayed during a videotaped standardized anamnesis protocol.
Results: Symptomatic athletes spend significantly more time with *act apart* hand movements and less time with *closed* rest positions when compared to non-concussed athletes. Post-concussion symptom (PCS) scores positively correlate with *act apart* hand movements. A linear regression analysis revealed that *act apart* hand movements significantly predict the PCS score.
Conclusions: Athletes with increased symptoms after mTBI move their hands in a hyperactive and restless manner. Increased *act apart* hand movements, i.e., when both hands move simultaneously without touching each other, indicate a motoric destabilization in symptomatic athletes' behaviour that might be related to impaired inhibitory motor control systems. Future diagnoses should concern the systematic analysis of the nonverbal movement behaviour as a potential behavioural marker of symptoms after mTBI.

1. Introduction

Although mild traumatic brain injuries (mTBI) in sports, which are often used interchangeably with the term concussion, are recognized as a major public health concern [1], mTBIs often remain undiagnosed because of the absence of obvious focal brain lesions and the non-existence of a valid and reliable diagnostic criteria [2,3]. Therefore, multiple symptom scales and assessment tools have been proposed in order to assess potential alterations of an athlete's health status after a mTBI in sports [3–5]. Although athletes with multiple concussions have been described as agitated or restless [6–8], the nonverbal movement behaviour of individuals with mTBI has not been investigated with objective methods.

Athletes with multiple concussions and (post-mortem) diagnoses of chronic traumatic encephalopathy (CTE) have been described as agitated and/or restless years before death [6–8]. In fact, McKee et al. described a world champion boxer with repetitive head trauma (and post-mortem diagnosed CTE) as restless and agitated more than 10 years before death [7]. The case report of a boxer with neuropathologically confirmed dementia pugilistica has also been portrayed as restless and agitated 13 years before death [8]. Children who experienced a mild head injury of sufficient severity to warrant temporary hospitalization between the ages of 0–10 years were likely to show increased hyperactivity/inattention at 10–13 years of age when rated by both mothers and teachers [9]. A recent meta-analysis also documented an association between mTBI and attention deficit hyperactivity disorder (ADHD) [10]. When using the *Behavior Change Inventory* (BCI), Hartlage et al. reported by using self-reports as well as reports from reference persons (e.g., spouse, close family member) that individuals with mTBI behaved more agitated, less calm, more

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depressed, more irritable, more slow, more tired, less energetic, etc. from pre- to post-injury [11]. Thus, the behaviour of concussed individuals seems to be characterized by hyperactive, restless, and/or agitated behaviour which is similarly described in a variety of psychiatric and medical illnesses [12–16].

In contrast, the investigation of the excitability and inhibition of the motor cortex in athletes who have experienced multiple concussions showed that mTBIs resulted in the reduced excitability of the motor cortex [17] or prolonged cortical silent periods [18]. A greater intracortical inhibition indicates that movement behaviour should be reduced as a post-concussion alteration. We therefore investigate in the present study whether symptoms after mTBI in sports are characterized by a hyper- or hypoactive movement behaviour.

A behavioural marker of hyperactivity according to the DSM-5 Diagnostic Criteria is when an individual often fidgets or taps hands when sitting [14]. Agitation has been defined as excessive motor activity associated with a feeling of inner tension [19]. Agitated activity is usually non-productive and repetitious and consists of behaviours such as pacing, fidgeting, wringing of the hands, pulling of clothes, and inability to sit still [19]. Restlessness has been described as the desire to move the legs or arms (mostly associated to restless legs syndrome) [20]. A study that investigated systematically the movement behaviour in patients with social phobia reported increased restlessness by shorter rest positions of the two hands, particularly shorter closed rest positions [16]. Shorter closed rest positions in patients indicate less psycho-motor stability as healthy individuals often display closed hand movements in situations when mental concentration is necessary [21]. Thus, a common movement pattern of hyperactive, agitated, and/or restless individuals seems to be displayed by increased hand motor activity and shorter hand rest positions.

Contrasting to the assumption that behavioural alterations exist after mTBIs, parents did not observe a different movement behaviour for categories such as „fidgety "or „restlessness "in their own children with mTBI [22]. However, parental perceptions of potential hyperactive behaviour in their own children have been described as not very reliable because parents recognized approximately only 50 % of a hyperactive group [23]. In fact, when analysing nonverbal hand movement behaviour regarding its neuropsychological functions raters need to be trained in order understand and correctly rate or analyse movement behaviour [21] as ratings of non-experts often rely on (wrong) stereotyped beliefs about nonverbal indicators [24]. As this methodological constraint accounts for all previous studies that investigated potential behavioural alterations of concussed individuals [6–9,11,22], the intention of the present study is to investigate the nonverbal movement behaviour of athletes with mTBI by a systematic and sensitive movement analysis of videotaped concussion anamnesis protocols and trained and certified raters of an established neuropsychological hand movement analysis system [21,25].

Because of the hyperactive (/agitated/restless) behaviour observed in athletes with multiple concussions [6–9,11], we hypothesized that symptomatic athletes with mTBI would display increased nonverbal hand movement activity (Hypothesis 1 (H1)). Furthermore, because shorter *closed* rest positions particularly indicate a higher restlessness in patients [16], we secondly explore the hypothesis (H2) that symptomatic athletes are characterized by less *closed* rest positions.

2. Methods

2.1. Participants

40 athletes (mean age: 22.7 ± 4.5; 13 female, 27 male; average years of sports participation: 9.2 ± 5.8; Table 1) from various sports (American Football (N = 14), field / ice hockey (N = 12), boxing (N = 5), rugby (N = 4), soccer (N = 2), handball (N = 2), climbing (N = 1)) participated in the study as part of an ongoing concussion assessment protocol (the protocol was installed at the German Sports University of Cologne, Germany in 2017). Participants were recruited via cooperation with local sports-clubs for concussion assessment and baseline protocols. Written informed consent was obtained from each participant (by the researchers) before the investigation. The participants were particularly pointed to the fact that they could retract from their participation at any time. Because addressing the investigation of hand movement behaviour before the interview would affect the participants' spontaneous behaviour, we clarified the intent of the study that nonverbal behaviour is part of the data analysis after all measurements of the protocol were performed. The local Ethics Committee of the German Sport University approved the study.

Concussed participants (N = 28; mean age: 23.5 ± 4.7; 8 female, 20 male) concerned athletes with self-reported post-concussion symptoms (N = 14) and without symptoms (N = 14). Non-concussed matched athletes (matched in age, gender, years of sports participation, and years of education; N = 12, mean age: 20.6 ± 3.4; 5 female, 7 male) served as a control group. The two participant groups with mTBI were matched according to their age, time post-concussion, and the amount of experienced concussions. I.e., there were no significant differences (mean time post-concussion = 22.0 ± 46.5 months; mean amount of experienced concussions = 1.8 ± 0.9). Matching (/coding of movement behaviour) was performed post hoc after a substantial amount of videotaped symptomatic athletes participated in the study. As soon as the minimum amount of participants was reached we started to match asymptomatic and non-concussed participants from the ongoing anamnesis protocol to the symptomatic group. This resulted in the behavioural analysis of 40 participants from an entire dataset of 53 videotaped individuals.

Concussions were assessed using self-reports according to the definition of the consensus statement on concussion in sport [26]. The symptom assessment scale of the "Sport Concussion Assessment Tool – 3rd edition" (SCAT3) [27] was used to register participants post-concussive symptoms. In this likert-like symptom scale, each symptom is rated from 0 ("none") to 6 ("severe"). The number of 22 symptoms is summated to a post-concussion symptom score (PCS score) with a maximum of 132 (22 × 6). We used a PCS score of 10 as a cut-off to differentiate between symptomatic and asymptomatic (concussed) athletes as previous studies reported 8 or 10 points for baseline (/low symptoms) results [28].

2.2. Interview situation

Participants were interviewed using a standardized questionnaire to obtain the athletes sports participation, age, education, handedness, occurrence of a mild traumatic brain injury, description of the incident, time post-concussion, and regarding the presence or absence of post-concussive symptoms using the symptom scale of the SCAT3. If athletes answered "no" to the 'occurrence of a mild traumatic brain injury' question (non-concussed athlete group), they were asked "if they observed concussions in their sport and how the incident happened". The interview was recorded using a digital video camera (Canon Powershot G10) placed 3 m in front of the interviewee. The interview took place in a quiet room (without windows) at the Department of Neurology, Psychosomatic Medicine, and Psychiatry of the German Sports University and was performed by the principle investigator.

2.3. Measurements

In the on-going stream of nonverbal movement behaviour all occurring hand movements and rest positions (Activation category) were coded using the NEUROGES-Elan coding system [25] during the anamnesis (e.g., the description of the concussive incident) and the symptom assessment of the interview (mean lengths of interviews = 4 min 34 s ± 2 min 5 s (Minimum: 2 min 3 s; Maximum: 13 min 9 s). The stream of hand movement behaviour is therefore segmented into movement units (*movement*) versus no-movement (*rest/*

Table 1
Short definitions of hand movement categories, values, and definitions (according to Lausberg [25]) and the inter-rater agreements (IA) for each value (according to Holle and Rein [29]).

Category	Value	Short definition	IA (/raw agreement)
Activation	*movement*	hands are in active motion	0.60
	rest/pose	hands rest or pose	0.72
Rest/pose	*crossed*	in rest or pose position: the knuckles of the right and left hands are crossed	0.80 (/0.97)
	closed	in rest or pose position: the right and left hands touch each other but the knuckles hands are not crossed	0.83 (/0.94)
	open	in rest or pose position: the right and left hands do not touch each other and the knuckles hands are not crossed	0.83 (/0.96)
Contact	*act on each other*	the hands dynamically touch each other	0.68 (/0.85)
	act as a unit	the two hands are in touch with a fixed configuration and they take a joint action	0.45 (/0.94)
	act apart	both hands move simultaneously without touching each other	0.68 (/0.84)

Fig. 1. Exemplary rest positions.

pose) units based on the criteria motion vs. stillness, actively held position vs. gravity-aligned / supported position, muscle contraction vs. relaxation. All muscle contractions, which immediately affect finger, wrist, elbow or shoulder joints are considered. The Activation category provides a general impression of an individual' s level of (psycho)motor activity as any appearing left- or right-hand movement is coded. A rest position was defined as a specific arrangement of the relaxed limbs characterized by motionless, absence of an anti-gravity position, and muscle relaxation [25]. In the next step, the bilateral *rest/pose* units are then classified into three rest position values: *crossed, closed, open* (Fig. 1). The simultaneous movement of two hands is further operationalized by the presence/absence of physical contact between the hands and the quality of that contact (Contact category). Therefore, three Contact values are distinguished: *act apart, act as a unit,* and *act on each other*. *Act apart* refers to sequences in which both hands move but do not touch each other, e.g. when forming both hands in order to describe the shape of a ball. *Act as a unit* refers to sequences in which the right and left hand establish static contact during a complex phase, e.g. when praying. *Act on each other* refers to sequences in which at least one hand has dynamic contact to the other hand, e.g. when fidgeting or the hands are rubbing each other (Table 2).

2.4. Inter-rater agreement (IA)

Four independent (and naive to the research question) raters were trained and certified to analyse hand movement behaviour according to NEUROGES [25]. NEUROGES training took place in three separate multi-day workshops organized by experienced raters (/researchers) that are using NEUROGES. The NEUROGES rater training consists of three components: a detailed theoretical introduction to movement behaviour research, movement exercises, and a proper coding training. A NEUROGES certificate was achieved by rating several training videos with a minimum of overlap with expert ratings of 60 percent. The videos were analysed without sound to avoid raters of being biased by verbal information. For each video, one rater coded 100 % of the data for statistical analysis whereas the second rater coded 25 % of the data to establish IA. IA for Activation was calculated as the ratio between total length of overlaps from both annotators and total length of movement units from both annotators [21]. IA on the Rest/pose and Contact values was established by calculating a modified Cohen's kappa according to Holle and Rein [29]. This modified Cohen's kappa takes into account not only the categorization of values but also the temporal overlap of the raters' annotations. Results of the IA are presented in Table 2. The raw agreement represents the number of agreeing cases

Table 2
Participants (*significant differences between groups; n.s. = not significant).

	Non-concussed athletes	Concussed athletes		Statistics between groups
		Symptomatic athletes	Asymptomatic athletes	
N	12	14	14	
Gender (female/male)	5 / 7	5 / 9	3 / 11	n.s., $\chi^2(2) = 1.308$, p = 0.520
PCS score*	3.7 ± 3.3	30.0 ± 15.0	3.7 ± 3.3	*F(2, 39) = 36.507, p < 0.001
Age	20.6 ± 3.4	24.6 ± 5.0	22.4 ± 4.1	n.s., F(2, 39) = 2.902, p = 0.067
Time post concussion (months)	–	11.5 ± 17.2	32.5 ± 62.9	n.s., t(26) = 1.204, p = 0.239
Amount of concussions	–	2.0 ± 1.0	1.6 ± 0.9	n.s., t(26) = −1.194, p = 0.243
Years of sport participation	9.7 ± 7.0	9.9 ± 5.7	8.0 ± 4.8	n.s., t(26) = −1.966, p = 0.343
Education (years)	12.2 ± 1.4	11.6 ± 1.5	12.3 ± 1.3	n.s., t(26) = −1.662, p = 0.109

divided by the total number of cases. In particular with regard to the fact that the modified Cohen's kappa does not only consider the raters' agreement concerning the value but also the segmentation of behaviour in time, i.e., if there is a unit and when it begins and ends, the agreement in the present investigation was "substantial/almost perfect" (in terms of Landis and Koch [30]) with reference to classical kappa scores [25].

2.5. Statistics

The data were exported and analysed according to the guidelines for analyses with NEUROGES–ELAN system [25]. We performed univariate and repeated measures analyses of variance (u/rmANOVAs) using SPSS (IBM SPSS Statistics version 25) for normally distributed variables only and with Greenhouse-Geisser corrections when the assumption of sphericity was violated. The between-subjects factor constituted group, i.e., athletes without a history of a mTBI ("non-concussed"), concussed athletes with a PCS score < 10 ("asymptomatic"), and concussed athletes with a PCS score > 10 ("symptomatic"). In order to find out whether symptomatic athletes would present increased movement *activity*, the proportion of time (seconds per minute; PoT) of right and left hand movements were used as a dependent variable in an uANOVA. The PoT of hand movements (/rest positions) was calculated by the division of the duration of occurring hand movements (/rest positions) and the individual duration of the interview. Thus, the dependent variable PoT provides information how much time (in seconds) an individual spends with a certain hand movement (/rest position) per minute. To contrast hyper- vs. hypo-activity, the PoT of hand movement Activation and rest positions served as the dependent variable "activation" (*movement, rest/pose*). To find out whether symptomatic athletes would present increased *act apart* hand movements, the PoT of the Contact values (*act apart, act on each other)* served as the dependent variable in a rmANOVA (the variable *act as a unit* was excluded from further analysis due to the violation of normal distribution). In order to find out whether symptomatic athletes would present less *closed* rest positions, the PoT of rest position values (*closed)* were used as the dependent variable in an uANOVA (the variables *open* and *crossed* were excluded from further analysis due to the violation of normal distribution). Multiple post hoc pairwise comparisons were corrected with Bonferroni corrections. To determine a relationship of movement behaviour and post-concussion symptoms, we calculated the Pearson's correlation coefficient (r_p) for parametric and the Spearman correlation coefficient (r_s) for non-parametric data (single symptoms). To gain insights whether a particular behavioural category would predict post-concussion symptoms, we additionally calculated a linear regression analysis. A summary of the findings in relation to the formulated hypotheses is provided in Table 3.

3. Results

Symptomatic athletes present significantly higher PCS scores ($F(2, 37) = 36.507$, $p < 0.001$; (mean) PCS = 30.0 ± 15.0) when compared to asymptomatic ($p < 0.001$; PCS = 3.7 ± 3.3) and non-concussed athletes ($p < 0.001$; PCS = 3.7 ± 3.3). The most frequently reported symptoms in the symptomatic athlete group were "difficulty concentrating" (n = 13), "feeling slowed down" (n = 10), "fatigue or low energy" (n = 10), "sensitivity to light" (n = 9), "drowsiness" (n = 9), and "headaches" (n = 9).

3.1. Hypothesis 1: symptomatic athletes with mTBI display increased nonverbal hand movement activity

3.1.1. Activity

No significant effects were found for hand movement *activity* between groups ($F(2, 37) = 2.639$, $p = 0.085$, $\eta^2 = 0.125$).

3.1.2. Activation

Significant effects were found for *activation* ($F(1, 37) = 135.297$, $p < 0.001$, $\eta^2 = 0.785$) independently from group. Post-hoc comparisons revealed that all athletes spent significantly more time with hand movements (mean [M] ± standard error [SE]: 35.5 ± 2.0) than with rest positions (M ± SE: 7.3 ± 0.5; $p < 0.001$).

3.1.3. Contact

Significant effects were found for *contact* ($F(1, 37) = 6.644$, $p < 0.05$, $\eta^2 = 0.152$), and for the interaction of group and *contact* ($F(2, 37) = 6.021$, $p < 0.01$, $\eta^2 = 0.246$). Post-hoc comparisons revealed that all athletes spend significantly more time with *act on each other* (M ± SE: 12.2 ± 1.3) when compared to *act apart* movements (M ± SE: 8.3 ± 0.8; $p < 0.05$). Post-hoc comparisons of the interaction effect showed that symptomatic athletes spend significantly more time with *act apart* movements (M ± SE: 12.3 ± 1.4) when compared to non-concussed athletes (M ± SE: 4.3 ± 1.5; $p < 0.01$; Fig. 2).

3.2. Hypothesis 2: symptomatic athletes are characterized by less closed rest positions

3.2.1. Rest positions

Significant effects were found for *closed* rest positions ($F(2, 40) = 5.037$, $p < 0.05$, $\eta^2 = 0.214$). Post-hoc comparisons revealed that symptomatic athletes spent significantly less time with *closed* rest positions (M ± SE: 10.5 ± 2.8) when compared to non-concussed athletes (M ± SE: 23.6 ± 3.0; $p < 0.01$; Fig. 3).

Table 3
Summary of findings with regard to the formulated hypotheses.

Hypothesis	Result	Hypothesis supported
Symptomatic athletes with mTBI display increased nonverbal hand movement activity.	Movement: No significant differences exist between groups regarding the general hand movement activity. Contact: Symptomatic patients displayed significantly more *act apart* hand movements than non-concussed patients.	Partially
Symptomatic athletes are characterized by less *closed* rest positions.	Symptomatic athletes spent significantly less time with *closed* rest positions when compared to non-concussed athletes.	Yes
Hand movement behaviour and post-concussion symptoms are related.	It exists a positive correlation between the PCS score and *movement*. It exists a negative correlation between the PCS score and *closed* rest positions. It exists a positive correlation between the PCS score and *act apart* hand movements.	Yes
Prediction: Hand movement behaviour predicts post concussion symptoms.	*Act apart* hand movements significantly predict the PCS score.	Partially

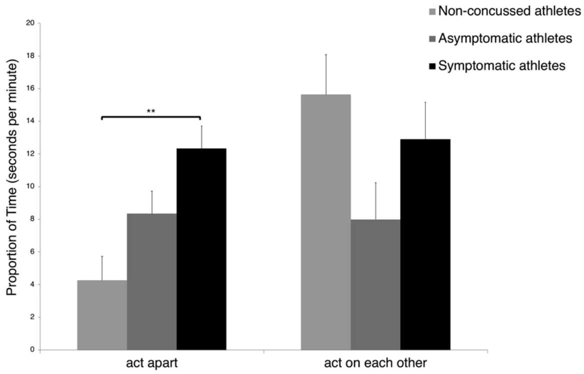

Fig. 2. Proportion of time (PoT) of the Contact values (*act apart, act on each other)* of symptomatic, asymptomatic, and non-concussed athletes.

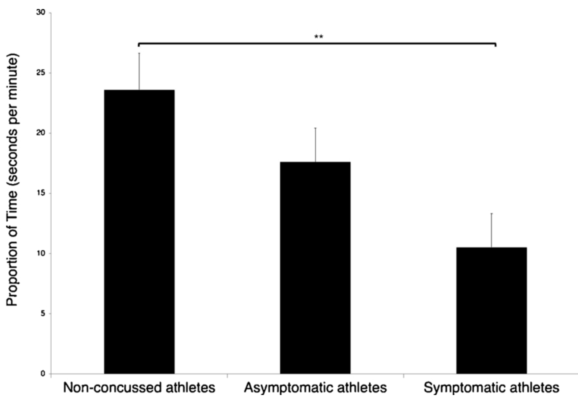

Fig. 3. Proportion of time (PoT) of *closed* hand rest positions of symptomatic, asymptomatic, and non-concussed athletes.

3.3. Hypothesis concerning the link between movement behaviour and post-concussion symptoms

3.3.1. Correlation/regression analysis

It exists a significant positive correlation between the PCS score and *movement* ($r_p(40) = 0.418$, $p < 0.01$), a significant negative correlation between the PCS score and *closed* rest positions ($r_p(40) = -0.344$, $p < 0.05$), and a significant positive correlation between the PCS score and *act apart* hand movements ($r_p(40) = 0.640$, $p < 0.001$). A linear (stepwise) regression with the PCS score as the dependent variable and *movement*, *closed* rest positions, and *act apart* hand movements as the independent variables revealed significance ($F(1, 39) = 26.331$, $p < 0.001$, $R^2 = 0.409$), i.e. *act apart* hand movements significantly predict the PCS score ($\beta = 0.640$, $t = 5.131$, $p < 0.001$; Fig. 4).

Further analyses revealed that *act apart* contacts are positively correlated to the symptoms "pressure in the head" ($r_s(40) = 0.358$, $p < 0.05$), nausea ($r_s(40) = 0.336$, $p < 0.05$), "don't feel right" ($r_s(40) = 0.428$, $p < 0.01$), "fatigue or low energy" ($r_s(40) = 0.462$, $p < 0.01$), confusion ($r_s(40) = 0.326$, $p < 0.05$), drowsiness ($r_s(40) = 0.441$, $p < 0.01$), "trouble falling asleep" ($r_s(40) = 0.331$, $p < 0.05$), irritability ($r_s(40) = 0.352$, $p < 0.05$), sadness ($r_s(40) = 0.327$, $p < 0.05$), and nervous or anxious ($r_s(40) = 0.342$, $p < 0.05$).

4. Discussion

This research revealed that symptomatic athletes with mTBI spent significantly more time with *act apart* hand movement contacts and significantly less time with *closed* rest positions when compared to non-concussed athletes. Although hand movement activity, *closed* rest positions, and *act apart* contacts are correlated to post-concussion

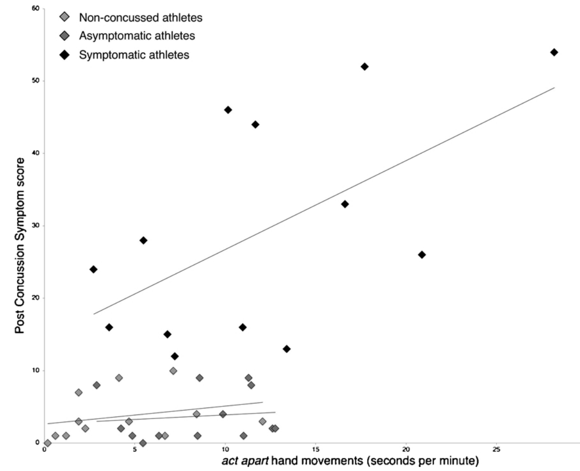

Fig. 4. Significant correlation of both hand (bh) *act apart* hand movements and post-concussion symptom (PCS) scores.

symptoms, only *act apart* hand movement contacts significantly predicted the PCS score. In fact, *act apart* contacts are correlated to the symptoms "pressure in the head", nausea, "don't feel right", "fatigue or low energy", confusion, drowsiness, "trouble falling asleep", irritability, sadness, and nervous or anxious.

This is the first study that showed that hand movement activity such as *act apart* hand movements, and *closed* rest positions differs between symptomatic mTBI athletes and non-concussed athletes. Thus, in contrast to non-concussed athletes, symptomatic mTBI athletes move their hands in a hyperactive and restless manner. Athletes with multiple concussions (and (post-mortem) diagnoses of CTE) have been described as hyperactive (/restless/agitated) [6–8], however, it has never been systematically analysed with standardized methods of nonverbal movement behaviour whether post-concussion symptoms are related to hyperactivity/restlessness and how that behaviour is particularly expressed. The fact that hyperactive/restless behaviour has been described in the cases that were later diagnosed with CTE [6–8] points out that nonverbal hand movements might serve as a behavioural marker of post-concussion symptomatology.

The behavioural pattern of increased *act apart* hand movements and decreased *closed* rest positions in symptomatic athletes with mTBI might not only indicate hyperactive (/restless) movement behaviour but also points to a destabilized behaviour [21]. When resting in *closed* positions a person remains psycho-motorically stable as healthy individuals often display *closed* positions in situations when mental concentration is necessary [21]. Because concentration deficits are common after mTBI in sports [31] and mothers and teachers would rate children with mild head injuries as hyperactive/inattentive [9], the present findings provide evidence (by the systematic analysis of nonverbal behaviour) that symptomatic mTBI athletes act destabilized.

Furthermore, *act apart* hand movements correlated with several post-concussion symptoms such as "pressure in the head", nausea, "don't feel right", "fatigue or low energy", confusion, drowsiness, "trouble falling asleep", irritability, sadness, and nervous or anxious. Previous studies showed that alterations of hand movements were related to depressive symptoms [32,33]. Because mental disorders such as depression and emotional disturbances are related to mTBI [34,35] and are characterized by similar symptoms [36], the present finding of altered movement behaviour in symptomatic mTBI athletes might be indicative of the development persistent post-concussion difficulties that overlap in part with depressive disorders. The self-reported symptom drowsiness in particular represents a feeling of being sleepy and lethargic commonly described as sleepiness [37]. This might contradict the observations of hyperactive and restless hand movement behaviour of the present symptomatic athletes, however, excessive daytime sleepiness has been previously described in adults with possible ADHD [38] and also with TBI [39]. Because ADHD as well as mTBI have been also linked to problems with response inhibition [40,41], the hyperactive and restless hand movement behaviour of symptomatic athletes in the present study might therefore be grounded in impaired inhibitory control to impulsive motor behaviour. In fact, a recent study showed that patients with mTBI without apparent difficulties in performing complex attention-demanding but routine tasks may experience long-lasting deficits in regulating inhibitory control during situations that necessitate rapid conflict resolutions [42]. Thus, and in contrast to previous reports of reduced excitability of the motor cortex [17] or prolonged cortical silent periods [18], the present data indicate (in contrast to self-reports of for example drowsiness) that symptomatic mTBI athletes represent a deficit of motor response inhibition.

4.1. Practical implications

Because of the fact that athletes frequently dissimulate post-concussive symptoms in order to keep on playing [43], the present data might help to better understand athletes with post-concussion symptoms. Thus far, behavioural analyses are not included in regular post-concussion assessment protocols [3]. When using the *Behavior Change Inventory* (BCI) with 68-items, individuals with mTBI were described (by self-evaluation and external appraisal) as more agitated, less calm, more depressed, more irritable, more slow, more tired, less energetic, etc. from pre- to post-injury [11]. In the present study, most frequently self-reported symptoms of symptomatic athletes were “difficulty concentrating”, “feeling slowed down”, “fatigue or low energy”, “sensitivity to light”, “drowsiness”, and “headaches”. Thus, commonly used symptom scales assess movement behaviour of athletes only indirectly providing indeterminate information about potential alterations of motor patterns. In fact, someone might even assume that the movement behaviour might be reduced according to the self-reported symptoms (e.g., drowsiness, fatigue or low energy, etc.). The systematic investigation of nonverbal hand movements and rest positions therefore provides more sensitive information about an athlete’s movement and resting behaviour and therefore an athlete’s health status. Thus, in contrast to ratings such as “more slow” or other self-reported symptoms that would indicate slower or reduced physical movement behaviour, the systematic analysis of the nonverbal hand movement activity and rest positions indicates a hyperactive and restless behaviour in symptomatic athletes with mTBI that might be grounded in abnormalities of inhibitory motor control systems. Although the present analysis of nonverbal behaviour by two (naïve to the research question and) trained raters is still time-consuming for the application in clinical assessment protocols of mTBI in sports, it serves to gain detailed information about an athlete’s behaviour in relation to the athletes health status that cannot be assessed by self-reports. Because ongoing research intends to assess nonverbal movement production via automatized movement detection algorithms [44], future assessments might be able to provide relatively quick insights about potential alterations of nonverbal behaviour of athletes with or without mTBI in sports via motion tracking. Automatized movement detection algorithms would also allow to overcome the restriction of relatively low sample sizes as in the present study. However, a fine-grained movement analysis of different movement categories as in this investigation cannot be performed via automatized movement detection yet.

4.2. Limitations

The present investigation comprises some limitations that need to be addressed such as the non-existing information about other potential disorders (such as depressive symptoms, CTE, or ADHD) of the present individuals, the time delay of the experienced concussion of the athletes, and the performed behavioural analysis. As previously described, depressive disorders, CTE, or ADHD are characterized by altered behaviour, thus, future studies are necessary to address whether nonverbal behaviour of athletes is indicative of post-concussion symptoms in particular and can therefore be differentiated from the behaviour when suffering from other disorders. Particularly the fact that we did not find a significant difference between symptomatic and asymptomatic mTBI athletes points out that more research is necessary to ascertain whether altered nonverbal movement behaviour of athletes with mTBI constitutes a fundamental consequence of the injury that might be indicative of post-concussive difficulties independent of self-reported symptoms. Furthermore, to gain insights about the health status of a concussed athlete and potential behavioural alterations of mTBI, future analyses of nonverbal hand movements should be assessed before, immediately after, and after the remission of symptoms of a mTBI. This design would enable clinicians and researchers to answer health related questions of mTBI in sports individually in order to improve post-concussion treatment protocols.

4.3. Conclusions

The present data showed that symptomatic mTBI athletes are characterized by hyperactive and restless hand movement behaviour, particularly by increased *act apart* hand movements and fewer *closed* rest positions when compared to non-concussed athletes. This hand movement behaviour not only evidences hyperactivity in athletes with mTBI but indicates abnormal motor response inhibition when suffering from post-concussion symptoms. Furthermore, as mTBI has been linked to problems with response inhibition, hyperactive and restless hand movement behaviour of symptomatic athletes indicates an impairment of inhibitory control to impulsive behaviour. The nonverbal hand movement behaviour might therefore serve as a behavioural marker of athletes with symptoms after mTBI. Because agitated/restless behaviour was previously described in concussed athletes who were later diagnosed with chronic traumatic encephalopathy, we suggest that future diagnoses should concern the detailed analysis of the nonverbal hand movement production as a potential behavioural marker of long-term effects after mTBI in sports.

CRediT authorship contribution statement

Ingo Helmich: Conceptualization, Methodology, Writing - review & editing. **Hedda Lausberg:** Conceptualization, Methodology.

Declaration of Competing Interest

We, the authors, are not in any professional relationship with companies or manufacturers who will benefit from the results of the present study. We declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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References

[1] D.J. Thurman, C.M. Branche, J.E. Sniezek, The epidemiology of sports-related traumatic brain injuries in the United States: recent developments, J. Head Trauma Rehabil. 13 (1998) 1–8, https://doi.org/10.1097/00001199-199804000-00003.

[2] M. McCrea, T. Hammeke, G. Olsen, P. Leo, K. Guskiewicz, Unreported concussion in high school football players: implications for prevention, Clin. J. Sport Med. 14 (2004) 13–17, https://doi.org/10.1097/00042752-200401000-00003.

[3] P. McCrory, W. Meeuwisse, J. Dvorak, M. Aubry, J. Bailes, S. Broglio, R.C. Cantu, D. Cassidy, R.J. Echemendia, R.J. Castellani, G.A. Davis, R. Ellenbogen, C. Emery, L. Engebretsen, N. Feddermann-Demont, C.C. Giza, K.M. Guskiewicz, S. Herring, G.L. Iverson, K.M. Johnston, J. Kissick, J. Kutcher, J.J. Leddy, D. Maddocks, M. Makdissi, G. Manley, M. McCrea, W.P. Meehan, S. Nagahiro, J. Patricios,

M. Putukian, K.J. Schneider, A. Sills, C.H. Tator, M. Turner, P.E. Vos, Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016, Br. J. Sports Med. 51 (2017) 838–847, https://doi.org/10.1136/bjsports-2017-097699 bjsports-2017-097699.

[4] J.T. Eckner, J.S. Kutcher, Concussion symptom scales and sideline assessment tools: a critical literature update, Curr. Sports Med. Rep. 9 (1) (2010) 8–15, https://doi.org/10.1249/JSR.0b013e3181caa778.

[5] P. McCrory, Sport concussion assessment tool 2, Scand. J. Med. Sci. Sports 19 (2009) 452, https://doi.org/10.1111/j.1600-0838.2009.00978.x.

[6] L.N. Hazrati, M.C. Tartaglia, P. Diamandis, K.D. Davis, R.E. Green, R. Wennberg, J.C. Wong, L. Ezerins, C.H. Tator, Absence of chronic traumatic encephalopathy in retired football players with multiple concussions and neurological symptomatology, Front. Hum. Neurosci. 7 (2013) 1–9, https://doi.org/10.3389/fnhum.2013.00222.

[7] A.C. Mckee, R.C. Cantu, C.J. Nowinski, T. Hedley-whyte, B.E. Gavett, A.E. Budson, E. Veronica, H. Lee, C.A. Kubilus, R.A. Stern, Chronic traumatic encephalopathy in athletes: progressive tauopathy following repetitive head injury, J. Neuropathol. Exp. Neurol. 68 (2009) 709–735, https://doi.org/10.1097/NEN.0b013e3181a9d503.Chronic.

[8] T.A. Kokjohn, C.L. Maarouf, I.D. Daugs, J.M. Hunter, C.M. Whiteside, M. Malek-ahmadi, E. Rodriguez, W. Kalback, S.A. Jacobson, M.N. Sabbagh, T.G. Beach, A.E. Roher, Neurochemical profile of dementia pugilistica, J. Neurotrauma 997 (2013) 981–997, https://doi.org/10.1089/neu.2012.2699.

[9] A. McKinlay, J.C. Dalrymple-Alford, L.J. Horwood, D.M. Fergusson, Long term psychosocial outcomes after mild head injury in early childhood, J. Neurol. Neurosurg. Psychiatry 73 (2002) 281–288 http://www.ncbi.nlm.nih.gov/pubmed/12185159.

[10] B.O. Adeyemo, J. Biederman, R. Zafonte, E. Kagan, T.J. Spencer, M. Uchida, T. Kenworthy, A.E. Spencer, S.V. Faraone, Mild traumatic brain injury and ADHD: a systematic review of the literature and meta-analysis, J. Atten. Disord. 18 (Oct. (7)) (2014) 576–584, https://doi.org/10.1177/1087054714543371.

[11] L.C. Hartlage, D. Durant-Wilson, P.C. Patch, Persistent neurobehavioral problems following mild traumatic brain injury, Arch. Clin. Neuropsychol. 16 (6) (2001) 561–570, https://doi.org/10.1016/S0887-6177(00)00067-6.

[12] A. Pierson, A. Par-Hot, R. Jouvent, C. Bungener, J. Martinerie, B. Renault, D. Widlocher, Loss of control of pre-motor activation in anxious agitated and impulsive depressives. A clinical and ERP study, Prog. Neuropsychopharmacol. Biol. Psychiatry 18 (Oct. (6)) (1994) 1037–1050, https://doi.org/10.1016/0278-5846(94)90129-5.

[13] E. Sacchetti, M. Amore, G. Di Sciascio, G. Ducci, P. Girardi, M. Mauri, A. Tortorella, L.M. De Matteis, C. Mencacci, Psychomotor agitation in psychiatry: an Italian expert consensus, Evid.-Based Psychiatr. Care 3 (2017) 1–24, https://doi.org/10.1093/nq/s13-I.25.488-a.

[14] C.R. Reynolds, R.W. Kamphaus, DSM-5™ Diagnostic Criteria, Diagnostic & Statistical Manual of Mental Disorders, (2013), https://doi.org/10.1176/appi.books.9780890425596.x00DiagnosticClassification.

[15] M.M. Brooke, K.A. Questad, D.R. Patterson, K.J. Bashak, Agitation and restlessness after closed head injury: a prospective study of 100 consecutive admissions, Arch. Phys. Med. Rehabil. 73 (Apr. (4)) (1992) 320–323, https://doi.org/10.2138/am-2018-6230.

[16] N. Neumann, I. Kreyenbrink, K.C.H. Reinecke, H. Lausberg, Hand rest positions of patients with social phobia and therapists in psychodynamic psychotherapy sessions (SOPHO- NET project), J. Multimodal Commun. 4 (2017) 50–55.

[17] A.V. Chistyakov, J.F. Soustiel, H. Hafner, M. Trubnik, G. Levy, M. Feinsod, Excitatory and inhibitory corticospinal responses to transcranial magnetic stimulation in patients with minor to moderate head injury, J. Neurol. Neurosurg. Psychiatr. 70 (May (5)) (2001) 580–587, https://doi.org/10.1136/jnnp.70.5.580.

[18] L. De Beaumont, M. Lassonde, S. Leclerc, H. Theoret, Long-term and cumulative effects of sports concussion on motor cortex inhibition, Neurosurgery 61 (2007) 329–336, https://doi.org/10.1227/01.NEU.0000280000.03578.B6.

[19] Cardwell C. Nuckols, American Psychiatric Association, Diagnostic and Statistical Manual of Mental Disorders, 5th Edition (DSM-5), Diagnostic and Statistical Manual of Mental Disorders 4th Edition TR. 35, (2013), pp. 1224–1232, https://doi.org/10.1176/appi.books.9780890425596.744053.

[20] American Psychiatric Association [APA], Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision (DSM-IV-TR), (2000), https://doi.org/10.1176/appi.books.9780890423349.

[21] H. Lausberg, Understanding Body Movement. A Guide to Empirical Research on Nonverbal Behaviour with an Introduction to the NEUROGES Coding System, Peter Lang Verlag, Frankfurt/Main, 2013, https://doi.org/10.1017/CBO9781107415324.004.

[22] L.K. Ayr, K.O. Yeates, H.G. Taylor, M. Browne, Dimensions of postconcussive symptoms in children with mild traumatic brain injuries, J. Int. Neuropsychol. Soc. 15 (2009) 19–30, https://doi.org/10.1017/S1355617708090188.

[23] E. Hutchinson, D. Pearson, C. Fitzgerald, B. Bateman, C. Gant, J. Grundy, J. Stevenson, J. Warner, T. Dean, S. Matthews, H. Arshad, P. Rowlandson, Can parents accurately perceive hyperactivity in their child? Child: Care Health Dev. 27 (2001) 241–250, https://doi.org/10.1046/j.1365-2214.2001.00214.x.

[24] A. Vrij, G.R. Semin, Lie experts' beliefs about nonverbal indicators of deception, J. Nonverbal Behav. 20 (1996) 65–80, https://doi.org/10.1007/BF02248715.

[25] H. Lausberg, The NEUROGES® Analysis System for Nonverbal Behaviour and Gesture, Peter Lang, Frankfurt am Main, 2019.

[26] P. McCrory, W.H. Meeuwisse, M. Aubry, R.C. Cantu, J. Dvorák, R.J. Echemendia, L. Engebretsen, K.M. Johnston, J.S. Kutcher, M. Raftery, A. Sills, B.W. Benson, G.A. Davis, R. Ellenbogen, K.M. Guskiewicz, S.A. Herring, G.L. Iverson, B.D. Jordan, J. Kissick, M. McCrea, A.S. McIntosh, D.L. Maddocks, M. Makdissi, L. Purcell, M. Putukian, K. Schneider, C.H. Tator, M. Turner, Consensus statement on concussion in sport-the 4th international conference on concussion in Sport Held in Zurich, November 2012, BMJ 5 (2013) 255–279, https://doi.org/10.1016/j.pmrj.2013.02.012.

[27] K.M. Guskiewicz, J. Register-Mihalik, P. McCrory, M. McCrea, K. Johnston, M. Makdissi, J. Dvorák, G. Davis, W. Meeuwisse, Evidence-based approach to revising the SCAT2: introducing the SCAT3, Br. J. Sports Med. 47 (2013) 289–293, https://doi.org/10.1136/bjsports-2013-092225.

[28] J.K. Chen, K.M. Johnston, A. Collie, P. McCrory, A. Ptito, A validation of the post concussion symptom scale in the assessment of complex concussion using cognitive testing and functional MRI, J. Neurol. Neurosurg. Psychiatry 78 (Nov. (11)) (2007) 1231–1238, https://doi.org/10.1136/jnnp.2006.110395.

[29] H. Holle, R. Rein, EasyDIAg: a tool for easy determination of interrater agreement, Behav. Res. Methods 46 (2014) 837–847, https://doi.org/10.3758/s13428-014-0506-7.

[30] J.R. Landis, G.G. Koch, The measurement of observer agreement for categorical data, Biometrics 33 (1977) 159–174, https://doi.org/10.2307/2529310.

[31] J. Biederman, L. Feinberg, J. Chan, B.O. Adeyemo, K.Y. Woodworth, W. Panis, N. McGrath, S. Bhatnagar, T.J. Spencer, M. Uchida, T. Kenworthy, R. Grossman, R. Zafonte, S.V. Faraone, Mild traumatic brain injury and attention-deficit hyperactivity disorder in young student athletes, J. Nerv. Ment. Dis. 203 (2015) 813–819, https://doi.org/10.1097/NMD.0000000000000375.

[32] H. Lausberg, M. Kryger, Gestisches Verhalten als Indikator therapeutischer Prozesse in der verbalen Psychotherapie: Zur Funktion der Selbstberührungen und zur Repräsentation von Objektbeziehungen in gestischen Darstellungen, Psychotherapie-Wissenschaft 1 (2011) 41–55.

[33] G. Ulrich, K. Harms, A video analysis of the non-verbal behaviour of depressed patients before and after treatment, J. Affect. Disord. 9 (1985) 63–67, https://doi.org/10.1016/0165-0327(85)90011-4.

[34] K.M. Guskiewicz, S.W. Marshall, J. Bailes, M. Mccrea, H.P. Harding, A. Matthews, J.R. Mihalik, R.C. Cantu, Recurrent concussion and risk of depression in retired professional football players, Med. Sci. Sports Exerc. 39 (2007) 903–909, https://doi.org/10.1249/mss.0b013e3180383da5.

[35] L.M. Mainwaring, S.M. Bisschop, R.E.A. Green, M. Antoniazzi, P. Comper, V. Kristman, C. Provvidenza, D.W. Richards, Emotional reaction of varsity athletes to sport-related concussion, J. Sport Exerc. Psychol. 26 (2004) 119–135, https://doi.org/10.1123/jsep.26.1.119.

[36] A. Eman Abdulle, J. van der Naalt, The role of mood, post-traumatic stress, post-concussive symptoms and coping on outcome after MTBI in elderly patients, Int. Rev. Psychiatry (2019) 1–9, https://doi.org/10.1080/09540261.2019.1664421.

[37] M.M. Kurtis, R. Balestrino, C. Rodriguez-Blazquez, M.J. Forjaz, P. Martinez-Martin, A review of scales to evaluate sleep disturbances in movement disorders, Front. Neurol. 9 (2018), https://doi.org/10.3389/fneur.2018.00369.

[38] W. Ito, Y. Komada, I. Okajima, Y. Inoue, Excessive daytime sleepiness in adults with possible attention deficit/hyperactivity disorder (ADHD): a web-based cross-sectional study, Sleep Med. 32 (2017) 4–9, https://doi.org/10.1016/j.sleep.2016.04.008.

[39] D.L. Parcell, J.L. Ponsford, S.M. Rajaratnam, J.R. Redman, Self-reported changes to nighttime sleep after traumatic brain injury, Arch. Phys. Med. Rehabil. 87 (2006) 278–285, https://doi.org/10.1016/j.apmr.2005.10.024.

[40] R.A. Barkley, Response inhibition in attention-deficit hyperactivity disorder, Ment. Retard. Dev. Disabil. Res. Rev. 5 (1999) 177–184, https://doi.org/10.1002/(SICI)1098-2779(1999)5:3<177::AID-MRDD3>3.0.CO;2-G.

[41] R.A.P. Roche, P.M. Dockree, H. Garavan, J.J. Foxe, I.H. Robertson, S.M. O'Mara, EEG alpha power changes reflect response inhibition deficits after traumatic brain injury (TBI) in humans, Neurosci. Lett. 362 (2004) 1–5, https://doi.org/10.1016/j.neulet.2003.11.064.

[42] B. Xu, M. Sandrini, S. Levy, R. Volochayev, O. Awosika, J.A. Butman, D.L. Pham, L.G. Cohen, Lasting deficit in inhibitory control with mild traumatic brain injury, Sci. Rep. 7 (2017) 14902, https://doi.org/10.1038/s41598-017-14867-y.

[43] W.B. Barr, M. McCrea, Diagnosis and assessment of concussion, in: F.M. Webben (Ed.), Handbook of Sport Neuropsychology, Springer Publishing Company, New York, NY, 2010.

[44] W.T.J.L. Pouw, J.P. Trujillo, J.A. Dixon, The quantification of gesture-speech synchrony: a tutorial and validation of multi-modal data acquisition using device-based and video-based motion tracking, Behav. Res. Methods (2018), https://doi.org/10.3758/s13428-019-01271-9.